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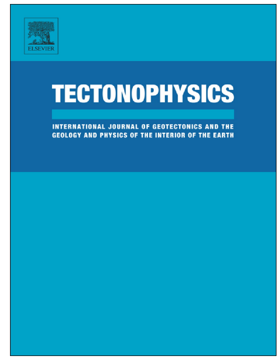

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Volcanic constraints on the unzipping of Africa from South America: insights from new geochronological controls along the Angola margin.

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Abstract

The breakup of Africa from South America is associated with the emplacement of the Paraná-Etendeka flood basalt province from around 134 Ma and the Tristan da Cunha plume. Yet many additional volcanic events occur that are younger than the main pulse of the Paraná-Etendeka and straddle the rift to drift phases of the main breakup. This contribution reports on new geochronological constraints from the Angolan part of the African Margin. Three coastal and one inland section have been sampled stretching across some 400 Km, with $^{39}Ar/^{40}Ar$, U-Pb and Palaeontology used to provide age constraints. Ages from the new data range from ~100 to 81 Ma, with three main events (cr. 100, 91 and 82-81 Ma). Volcanic events are occurring within the Early to Late Cretaceous, along this part of the margin with a general younging towards Namibia. With the constraints of additional age information both onshore and offshore Angola, a clear younging trend at the early stages of rift to drift is recorded in the volcanic events that unzip from North to South. Similar age volcanic events are reported from the Brazilian side of the conjugate margin, and highlight the need to fully incorporate these relatively low volume volcanic pulses into the plate tectonic breakup models of the South Atlantic Margin.

Introduction

The break-up between Africa and South America marks one of the classic pictures of continental separation. Due to the good geometrical fit between these two land masses, already recognized by Wegener (1915), much work has been undertaken to corroborate the pre-break up configuration, intraplate geometries, the early rifting phases, and the final separation of the continents (e.g., Untemehr et al. 1988; Mohriak *et al.* 1995; Jackson et al. 2000; Torsvik et al., 2009; Moulin et al., 2010; Heine et al. 2013; Gaina et al. 2013; Pérez-Díaz and Eagles, 2014; Kukla et al., 2018). Magmatism associated with the break-up is also important as it relates to the emplacement of the Paraná-Etendeka flood basalts and the volcanism associated with the volcanic rifted margin (e.g. Jerram and Widdowson 2005), yet the exact duration of magmatic events seem somewhat more complicated than a single pulse of activity associated with the Tristan da Cunha plume, and maybe more pulsed like that seen at other rifted margins such as Ethiopia-Yemen (e.g. Rooney 2017). On a general scale this should be a relatively simple break up story, but much debate still continues about the exact nature and timing of the rifting and separation of the land masses leading to the eventual onset of sea floor spreading. This is somewhat complicated due to the lack of clear reflectors in the Early stages of rifting (Cande & Kent 1995). Work aimed at reconstructing the conjugate salt basins of the margin has helped to constrain some of the major factors controlling break-up basin configuration (e.g. Torsvik et al., 2009; Strozyk et al., 2017; Kukla et al., 2018), though geochronological constraints in the later stages are sparse. A factor that further fuels the need to understand the very specifics of the separation, is the discovery of, and exploration for, major hydrocarbon reserves that are found within the sedimentary basins formed during the rift to drift separation of the continents (e.g. Szatmari and Milani, 2016; Masse and Laurent, 2016).

Concomitant with the onset of rifting of Africa from South America is the occurrence of the Paraná-Etendeka large igneous province (Jerram et al., 1999; Marsh et al 2001; Jerram & Widdowson 2005). This major volcanic event occurring at around 134 Ma (e.g. Dodd et al.2015; Svensen et al., 2017; Marsh and Swart, 2018), is associated with a large mantle anomaly, the trail of which can be seen today running along the Walvis ridge towards Tristan de Cuna. Although the main pulse of magmatism associated with this event is relatively well constrained to a 3-4 Ma period during the early phases of rifting, later stage magmatic activity related to the waning phase of flood volcanism (e.g. Jerram & Widdowson 2005), rift climax, break-up and sag phases, or indeed any volcanism unrelated directly with the rift to drift process, are poorly constrained on both margins. This is partly due to limited access to key exposures (buried in the offshore), and the nature of the magmatic events being of a relatively low volume in the proximal onshore sections, which leads to restricted availability of good geochronological constraints. Igneous events younger than the Paraná-Etendeka LIP have long been known to be present on the Brazilian margin (e.g. Nascimento et al., 2003; Mizusaki et al., 2002; Enrich et al., 2009; Guedes et al., 2005). Additional age constraints based on commercial well and seismic data in offshore Angola and Brazil can also be found (e.g. Mohriak and Leroy, 2012), and appear to be volumetrically significant in the latter phases of rifting (e.g. Higgins et al Submitted), but at present publications that address these younger units, particularly on the Angolan side, are limited.

The Angolan margin, north of Namibia, provides a key area where, until recently, access to important outcrops had been limited. Renewed exploration efforts along the margin, as well as improved access, particularly along coastal stretches, has allowed significant improvements to be made to our understanding of the preserved geology and tectono-stratigraphic timing relationships in Angola. This in turn has implications for understanding the rift to drift transition in Africa. The extensive salt deposits on the Angolan side as well as those found along the conjugate margin in Brazil, provide valuable information to determine the basin settings prior to and during the break up (Torsvik et al. 2009).

This short contribution reports on new geochronological constraints for Early to Late Cretaceous magmatism found along the Angolan margin as part of an extensive onshore basin analysis and stratigraphic study undertaken jointly by Statoil and Sonangol. Three main locations of magmatism have been identified and studied along ~400 km of the SW Angolan margin (Figure 1). The main goal of this study is to provide new age and geochemical data that can be utilized to constrain the rift to drift evolution of Africa from South America. The locations, stratigraphic context and general rock types of the three main study localities will first be introduced, as well as the methods used to constrain their ages. The results and a summary of the age significance of these magmatic events are then presented as well as palaeo-reconstructions of the rifting in order to place their spatial and temporal evolution in the context of continental break-up.

[Figure 1] a) Location maps of SW Angola showing the 3 main study locations. b) Casa Branca beach section, Sumbe, Kwanza Basin. c) Baía dos Elefantes and Serra de Neve, Benguela Basin. d) Bentiaba, Ponta Negra, Canico, Piambo and Uah sections, Namibe Basin. Additional features offshore indicated.

Geological constraints and sampling

Mesozoic volcanic rocks found within the onshore Angolan section of the West African margin are found almost exclusively within Cretaceous aged units. These have been identified as either pertaining to the main Paraná-Etendeka flood volcanics (e.g. Marzoli et al., 1999; Sharp et al., 2012; Gindre-Chanu et al., 2014; Marsh and Swart 2018), or as younger lower volume events with an alkali affinity (Marzoli et al., 1999). Eroded remnants of the Paraná-Etendeka Igneous Province occur as fault bounded blocks or isolated sill and dyke systems. Sections are exposed in the onshore Kwanza, Benguela and Namibe basins, and these sections are unconformably overlain by Aptian aged mixed carbonate-clastic evaporitc sections of the latest “Pre-Salt” (Cuvo Fm) and “Salt” succession (Loeme Fm.) in all 3 areas (Sharp et al., 2012: Gindre-Chanu et al., 2014). The Early to late Cretaceous succession, dominated by mixed carbonate-clastic and salt sequences, are grouped into; a pre-salt Aptian, a salt Aptian, and post salt succession ranging from Albian to Maastrictian (See figure 2).

Volcanic sections with clear Parana-Etendeka affinities have recently been described at the base of the Cretaceous on-shore Namibe Basin in SW Angola, termed the Bero Volcanic Complex, where they unconformably overly Precambrian basement or local fluvio-lacustrine sediments of assumed Jurassic to Permian age (Sharp et al., 2012; Gindre-Chanu 2014; Marsh & Swart 2018). Additional weathered and to some extent isolated segments of volcanic and intrusive units are also found in patches further north in Angola, including volumetrically significant sill and dyke systems stretching from Namibe to Benguela, and a large area of highly faulted outcrops SE of the town of Sumbe in the Kwanza Basin, both of which are interpreted to represent erosional remnants of the originally extensive Paraná-Etendeka LIP (cf. Marzoli et al., 1999).

[Figure 2] Stratigraphic context of the Cretaceous lithologies present along the Angolan margin. Section are generalised for the Kwanza Basin (left) and onshore Namibe Basin (right) (see also Gindre-Chanu et al., 2014).

Outcrops of volcanics of a younger age have been reported from onshore locations within the Kwanza Basin which produce low volume flows that are interbedded within stratigraphic units assigned to the Albian-aged Pinda Group. These flows have alkaline compositions (Marzoli et al., 1999). Comparable low volume flows have also been documented from the Namibe Basin (Carvalho and Soares, 1961; Sharp et al., 2012: Stragnac et al., 2014), where they are interbedded with strata of reported Santonian age. As part of a study to characterise the tectono-stratigraphic development of these younger volcanics along the Angolan margin, significant occurrences of volcanic units were identified, and over a period of several focused field campaigns between 2010 and 2014 were systematically described, sampled and correlated. Focus was on detailed facies description of igneous rock types present and facies and faunal content of sediments that are intercalated within, under and over the volcanic units. Three main sections are introduced here (e.g. figure 1). These sections run along a significant section (400 km+) of the SW Angolan coast and also slightly inland, and as such provide an extremely good spatial control (strike section) on late stage magmatism in Angola. The three key sections will briefly be described below.

Site 1. Casa Branca Beach Section, Sumbe, Kwanza Basin

The first studied set of exposures are located south of the town of Sumbe at a location known locally as Casa Branca (figure 1b). This is the same coastal section as briefly described by Marzoli et al. (1999). Exceptional coastal outcrops along the Casa Branca section, in particular the previously undescribed sections that extend 2km north and 1km south of Casa Branca (figure 3a), highlight a sub-marine depositional environment associated with shallow shelf to predominantly slope mixed carbonate clastic system characterized by a range of fossiliferous wackestone, grainstones to rudstones. Deposition in water depths of no more than 200m is envisaged. The section underlying the main igneous unit is characterized by a relatively monotonous shelfal succession of interbedded marlstones and micritic carbonates characterized by infaunal bivalves, echinoderms, pervasive grazing to dwelling trace fossils and occasional ammonites. Into this environment a submarine volcanic sequence (up to 70m thick) was emplaced consisting of pillow lavas and hyaloclastite deposits. In some instances there is significant interaction between the volcanics and the sediments including; inter pillow sediments, a minor volcanic hiatus with sediment interbed (ammonite bearing micrites), and spectacular sediment filled fissures that cut the volcanic pile.

The section overlying the main volcanic interval is characterized by a mixed carbonate-clastic succession of turbidites and slope channels rich in redeposited shallow marine allochems (peloids, ooids) and fauna (oysters, rudist bivalves, Nerinid gastropods), but also well-preserved ammonites. This succession passively onlaps and oversteps the volcanic succession with a passive drape character, and ultimately shallows up to high energy tidal to shoreface carbonate grainstones. Water depths are again interpreted to range from circa 200m (base of section) to a few m's (top of section). The sediment filled fissures that cut the volcanic pile are likely related to halokinesis, with the carbonates and volcanics interpreted as having slid on rafts which detached on the underlying Aptian-aged salt. Lithostratigraphically, the sedimentary succession below the volcanics is assigned to the Catumbela Fm, whilst the unit above the volcanics is predominantly assigned to the Quissonde Fm (Fig 2).

The sediment/volcanic interaction within this section provide excellent evidence of the emplacement environment as well as good stratigraphic control which will be discussed further. The volcanic rocks themselves consist of olivine/pyroxene rich basalts/alkali basalts, which in some instances are exceptionally fresh (e.g. Figure 3b).

Site 2. 2a – Serra de Neve. 2b - Baía dos Elefantes, Benguela Basin

The studied Benguela Basin sections comprises 2 distinct locations that are here grouped for briefness of documentation. These encompasses a large inland central volcanic complex (Serra de Neve), as well as a spectacular coastal section that extends along strike for over 10km between Baia dos Elefantes and Binga (see figure 1). The central Serra de Neve complex rises as a number of NW-SE striking high hills (over 2300 m elevation) with a main dominant central area at Serra de Neve (figure 3c). The complex comprises a number of cross cutting intrusive units including granites, phonolites, and mafic intrusions. The region was targeted for study as it falls along a clear NW-SE trending lineament from the coastal exposures of lava flows and shallow intrusions at Baia dos Elefantes. Importantly, the continuation of the NW-SE trending volcanic province is also evident in offshore seismic and potential fields data (gravity and magnetics). In this context it was thought that the volcanic centre at Serra de Neve, acted as an eruption centre feeding the coastal lava sequences. Within the central part of the main mountain large feldspar rich intrusive rocks were found (figure 3d). A number of rock samples were taken in and around the complex for study. No sediments were found to be associated with the Serra de Neve complex, with the exception of very poorly exposed lacustrine sediments within the central crater. No fossil content was recovered from these sediments.

Along the coastal section between Elefantes and Binga, excellent exposures of lava sequences entering a palaeo-coastline can be seen (figure 3e). These lavas are predominantly made up of large feldspar rich flows similar to the facies found within the volcanic centre (figure 3f). The lava sequences themselves are mainly sub-aerial flows but can be seen entering a shore-face environment and in places fragmenting to hyaloclastites. The nature of the sediments directly beneath the flows can be established as submarine slope and shallow shelf carbonates and marls, and are well exposed. Immediately underlying the main volcanic section is a 50-100m thick carbonate succession including high energy grainstone shoals, indicative of deposition in a shoreface to tidal setting. Shore face deposits immediately underlying the subaerial to sub-aqueous transition in the volcanics. Then a 100 m thick slope succession comprising infaunal echinoderms and a locally abundant well preserved ammonite fauna is found. The succession has an overall progradational character, and locally includes very well exposed slope-channel systems, some of which include volcanic derived clasts, indicative of coeval volcanism. Below this sequence is a mixed carbonate clastic shallow marine shelfal succession (Dondo and Catumbela Fm, see figure 2) comprising high energy grainstone shoals and subordinate thromobolite and rhod-algal units. The platform is grain dominated, with ooids, pelloids and rhodoliths dominating. The sandstones are quartz arenites. Growth faults are locally very well developed, interpreted as related to gravity gliding on the underlying salt. Shallow laccolith-like intrusives are evident intruding into the upper parts of the section associated with pepperite and soft sediment deformation – indicative of emplacement into relatively unconsolidated sediment. Seismic scale clinoform geometries within units exposed at Binga indicate depositional water depths at the time of deposition were circa 200 m, with accommodation space gradually being filled to sea level due to northwards progradation.

A 4km long North-South depositional dip section is exceptionally well exposed and accessible on the western side of Baía dos Elefantes, where the main volcanic units were samples for geochronology in this study (figure 3e).

Site 3. Namibe volcanics section (Bentiaba, Ponta Negra, Piambo, Cangulo, Uah, Mariquita).

The third main section of volcanics sampled in the present study comprises a number of coastal and inland sections exposed between the towns of Lucira in the north and Namibe in the south (Figure 1). The igneous units occur as a number of isolated flows, volcanic centres and subordinate intrusions. These are often found as cliff forming units along the coast north of Namibe (see figure 1), forming key stratigraphic markers within the sediments (e.g figure 3g). The lava flows can again be shown to be transitional from sub-aerial flows into shallow marine settings. At a location called Ponta Negra, one of the small volcanic centres occurs as an emergent volcano that feeds first hyaloclastites and then lava flows as it evolves (figure 3G). Here glassy basaltic fragments are quenched in the hyaloclastites (e.g. figure 3h), or can be sampled as microcrystalline lavas. Sediments interbedded with the volcanics include fluvial to shallow marine mixed carbonate-clastic successions. In a similar fashion to the Benguela coastal outcrops, east to west dip sections record a transition from subaerial to subaqeous conditions for both the sediments and extrusives. At Uah, Canico, Piambo and Mariquita the immediately underlying sediments are assigned to the Ponta Salinas Fm (Carvalho, 1961; Cooper, 1972, 1978), which include ammonite and shelly fauna bearing shelfal to shoreface successions. Pepperite successions are well exposed at Uah, Canico and Maraquita valleys, indicative of lava – wet sediment interaction. At Canico, invasive flows are also evident associated with soft sediment deformation, highlighting unequivocal evidence that the flows are within sequence and emplaced into the active sedimentary environment. These volcanics represent the southern most samples collected in this study. Stgnac *et al* (2014) termed these volcanics the Ombe Fm, whilst Sharp *et al* (2013) informally termed them the Bentiaba Basanite Fm. Carvalho (1961) was the first to document their occurrence, using the sections around Bentiaba as his type location.

At all three studied locations the volcanic sections contain relatively fresh rocks and can be seen to be of Early to Late Cretaceous age (Late Albian to Santonian) in the case of the lava sequences that are found within stratigraphy. The relative age of the Serra de Neve complex is less obvious to constrain as it appears to cut though basement rocks. The range of compositions for these volcanics is presented in Figure 4 along with the distribution of regional rocks compiled recently by Comin-Chiaramonti et al. (2011). They cover a wide range of compositions with many of the units showing an alkali affinity with alkali basalts, basanites and phonolites (figure 3). The next stage is to better constrain their geochronology in order to understand how these magmatic events fit within the context of break-up.

[Figure 3] a) View looking North along the Sumbe volcanics section at Casa Branca, Kwanza Basin. In view are pillow basalts and hyaloclastites interbedded with and overlain by a mixed carbonate-clastic slope succession of Latest Albian age. b) Example of exceptionally fresh olivine rich basalt from the Sumbe volcanics, Casa Branca section, Kwanza Basin. c) View from the edge of the Serra de Neve complex, Southern Benguela Basin. d) Large feldspar rich phonolite from the central intrusions within the Serra de Neve complex, Southern Benguela Basin . e) Coastal exposure at Baia dos Elefantes, Benguela Basin. At this location lavas overly shelfal to slope ammonite bearing carbonates of Latest Aptian age. f) close up of feldspar rich phonolite lava flow, as similar facies to that found in d. Baía dos Elefantes sections, Benguela Basin. g) Coastal section at Ponte Negra, Namibe Basin, comprising reowked hyaloclastits, invasive flows,

pillows and emergent volcanics immediately overlying sediments of the Salinas Fm of Coniacian to Santonian age. h) Hyaloclastites exposed at the Ponta Negra section, Namibe Basin.

[Figure 4] Total alkalis vs. silica diagrams for all analysed TAS classification diagram of the samples from this contribution. Overlain on top of a selection of representative rocks from the margin (after Comin-Chiaramonti et al., 2011). Numbered fields (volcanic-intrusive): 1) picrobasalt-picrogabbro; 2) basaltgabbro; 3) basaltic andesite-gabbrodiorite; 4) andesite-diorite; 5) dacite-granodiorite; 6) rhyolite-granite; 7) trachybasalt- monzogabbro; 8) basaltic trachyandesite–monzodiorite; 9) trachyandesite-monzonite; 10) trachydacite–quartz monzonite; 11) trachyte-syenite; 12) basanite/ tephrite–foid gabbro; 13) phonotephrite–foid monzogabbro; 14) tephriphonolite–foid monzosyenite; 15) phonolite–foid syenite; 16) foidite-foidolite (see also Comin-Chiaramonti et al., 2011) .

Geochronological methods

In order to place the Angola volcanic sections identified into the context of their evolution with respect to the separation of Africa from South America, samples were taken for geochronological control. The general geochemical affinity of the sample areas is presented in Figure 4, which highlights that a range of compositions exist from basalts to alkaline as well as some more evolved samples. A large part of the sections are dominated by basic composition rocks, and as such the majority of geochronological dating attempted was using the Ar/Ar system. Some of the evolved samples from the SN-BE area were also targeted for U/Pb analysis. Additionally, the stratigraphic and palaeontological knowledge of the area was used to help confirm confidence in the analysis results. The techniques used will be briefly summarised in the following subsections.

$^{40}Ar/^{39}Ar$ analysis

$^{40}Ar/^{39}Ar$ dating was carried out at the Open University. The samples were crushed using a pestle and mortar and the crushate was sieved and washed repeatedly in de-ionised water to remove dust and clay particles from the surfaces of all the size fractions. Using a binocular microscope, whole rock basalt chips were picked, selecting pieces free, from alteration, from samples with large, fresh and inclusion free feldspars, a feldspar separate was also picked for analysis from samples where this was possible. The picked separates were cleaned ultrasonically in acetone and de-ionised water, dried using a hot plate, and packaged in aluminium foil packets of ca. 10mm x 10mm in size prior to irradiation. Samples were irradiated at the McMaster Nuclear Reactor (McMaster University, Canada) for 100 hours. Cadmium shielding was used and the samples were held in position 8B. Neutron flux was monitored using biotite mineral standard GA1550, which has an age of 99.44 ± 0.17 Ma (Renne et al. 1998; Schmitz 2012).

The samples were step-heated using a 1059nm CSI fibre laser with the extracted gases passing through a liquid nitrogen trap and two SAES AP-10 getters (at 450°C and room temperature). After this, the gases were let into a MAP215-50 mass spectrometer for measurement. The mass discrimination was measured at 283 for $^{40}Ar/^{36}Ar$. System blanks were measured before and after every one or two analyses, and an average of the day’s blanks subtracted from the data. Results were corrected for 37Ar and 39Ar decay since irradiation and neutron-induced interference reactions, using the following correction factors: $(^{39}Ar/^{37}Ar)Ca = 0.00065 \pm 0.00000325$, $(^{36}Ar/^{37}Ar)Ca = 0.000264 \pm 0.000001325$, and $(^{40}Ar/^{39}Ar)K = 0.0085 \pm 0.0000425$ (based on analysis of K and Ca salts). The decay constants of Min et al. (2000) were used and all corrections carried out using in house data processing software and ages calculated using Isoplot (Ludwig, 2003). All age are reported at 2σ level and include the errors in the J value.

U/Pb analysis

U-Pb dating of zircons was carried out by Origin Analytical Ltd. using their standard methodology. Briefly, samples were disaggregated using a Retsch Jaw crusher and had heavy minerals separated from the 40-250 micron grain-size fraction using LST Heavy Liquid (2.95 g/mL). The dense fraction was then run through a Frantz magnetic separator and the non-magnetic fraction was mounted in araldite resin block and polished. The resin block was then placed into a Scanning Electron Microscope and mapped using electron dispersive spectroscopy to identify zircons in the sample. The identified zircons were then dated using quadrupole LA-ICPMS.

In order to correct for mass and instrumental bias, data were corrected against the Plesovice zircon standard (Sláma et al., 2008). During each run three Temora-2 (Black et al., 2004) and between three and ten 91500 (Woodhead et al., 2004) zircon standards were run as unknowns. Raw data were reduced using Iolite V3 software including correction for down-hole fractionation effects. To ensure that final data set contains U-Pb ages from zircons only, all data were screened for 178Hf counts as Hf is incorporated into zircon crystal lattice and is therefore abundant at the percent level in zircon (e.g. Belousova et al., 2006). All zircon ages were calculated using Isoplot (Ludwig, 2003) and ages with >10% discordance were rejected.

Stratigraphic and palaeontological control

The onshore sections of the central to southern coastal area of Angola have been subject to detailed field campaigns between 2010 and 2014, as part of a broader regional Statoil South Atlantic study addressing the onshore to offshore development of the South Atlantic margin in Angola and beyond. As part of this work, detailed stratigraphic correlations were undertaken on a basin by basin basis addressing the main syn, pre and post rift successions. A lithostratigraphic and chronostratigraphic template was established, and where possible, controlled using available biomarkers. A representative stratigraphic column for the onshore Namibe section is outlined in figure 2, and compared to the established Kwanza Basin stratigraphy. Key lithostratigraphic units are highlighted. In many of the Post Salt stratigraphic units ammonite biomarkers are present and help provide good general age constraints. Also by placing units within an Angolan margin scale sequence stratigraphic context, the relative timing of key basin wide events (e.g. salt basin development, base Pinda transgression, top Pinda flooding event etc.) are also better constrained. As each of the 3 main study locations within this contribution contain erupted volcanic sequences interbedded with fossiliferous sediments, then their relationships with-in the regional stratigraphy provides additional constraints and corroboration of any geochronological data.

Geochronological results

As introduced above the main geochronological data used within this contribution include the Ar/Ar and U/Pb systems as well as published and new stratigraphic/palaeontological control on within-stratigraphy volcanic flow units. Results from the three main study sections will be presented and then summarised before a consideration of these new results in the context of the unzipping of Africa from South America.

Casa Branca section, Kwanza Basin; $^{40}Ar/^{39}Ar$ -palaeontology

The Casa Branca Sumbe section provided some 3 km of outcrop with sediments intermingle with volcanic units emplaced in a submarine environment. Outcrops just inland from this section were also visited. Samples of the basalts were taken for $^{40}Ar/^{39}Ar$ analysis and additional stratigraphic biomarker information was also available to help build confidence in the results. Figure 5 a&b presents the $^{40}Ar/^{39}Ar$ result of a fresh whole rock analysis from the coastal section. This suggest that the age of this sequence is around 101.5 Ma, with the plateaux and invers isochron overlapping. An additional age from a sample from just inland gave an age of ~98.5 with more significant error in both the plateaux and inverse isochron age, and errors overlapping (see table 1).

One of the most striking observations made at this section was the occurrence of ammonites below, within and above the volcanic succession. Figure 5 c and d highlight an ammonite preserved within the inter-pillow section (unfortunately too poorly preserved to date). The ammonite zones within this area are relatively well known (e.g. Tavares et al 2007) and can help to provide additional information in consideration of the $^{40}Ar/^{39}Ar$ results. In short, well preserved ammonites collected during the course of this study in the section below the main volcanic section have typical Mid Albian ages, whilst new ammonite data (figure 5 e&f) from the sediments sitting immediately above the volcanics can be assigned with confidence to the last stage of the Late Albian (*Mortoniceras (Angolaites) gregory* (Spath, 1992). Upper Upper Albian, *M. (S.) rosratum* subzone, *vicina* horizon of Tavares et al., 2007 – giving an age of 99Ma). This age sits well with the volcanic age of 101 Ma (figure 5 a&b, table 1). Lithostratigraphically, the succession below the volcanics is assigned to the Catumbela Fm, whilst the succession that sits above the volcanics is assigned to the Quissonde Fm (Fig 2). It is interesting to note that the contact between the two formations is associated with a marked deepening and rotational faulting event in both onshore and offshore sections. The new data presented here indicates that the Sumbe volcanics are developed exactly at the boundary of the 2 formations, and could represent the driver for the basin wide change in depositional setting.

[Figure 5] Geochronology of the Casa Branca Beach Section, Sumbe. a & b) $^{40}Ar/^{39}Ar$ age with good overlapping plateaux and inverse isochron ~101.5 Ma. C & D) Ammonites within interpillow sediments. e, f & g) Ammonites from sediments directly above the volcanics - Mortoniceras (Angolaites) gregoryi (Spath, 1922), Upper Upper Albian, M. (S.) rosratum subzone (vicina horizon of Tavares et al., 2007 – giving an age of 99 Ma).

Serra de Neve – Baía dos Elefantes lineament: $^{40}Ar/^{39}Ar$ – U/Pb

The SN-BE lineament consists of two main sampling areas, the interior volcanic centre of Serra de Neve and the coastal sections around Baía dos Elefantes and Binga. Both areas are well exposed and a large range of good samples were available for analysis. Representative $^{40}Ar/^{39}Ar$ data are presented in figure 6 (a-d), and highlight a clustering of ages around 91 Ma (see also table 1 in summary section). The evolved samples within the Serra de Neve were also targeted to see if there were zircons present for U/Pb control. Figure 6e highlights some of the mineral separates and age analysis for these samples providing an additional U/Pb control age of 90.5Ma. Both these ages overlap providing good confidence in the geochronological data for this event. The stratigraphic control provided by the lava flows around the Baía dos Elefantes area suggest eruption from a subaerial into a submarine transition. New ammonite dating of samples taken within Unit 2, which sits some 50-110 m below the main lava flows, indicated a very tight age of the last stage of the Late Albian (*Mortoniceras (Angolaites) gregory* (Spath, 1992). Upper Upper Albian, *M. (S.) rosratum* subzone, *vicina* horizon of Tavares et al., 2007 – giving an age of 99 Ma). This is the same fauna and ammonite stage that was identified to sit ***above*** the main lava flow succession at Casa Branca. When the geochronological and palaeontological data are combined it appears clear that the volcanic event within the studied Benguela Basin section is several Myrs younger than that documented in the Kwanza Basin.

[Figure 6] Geochronology of the Serra de Neve – Baía dos Elefantes lineament. A-D) representative $^{40}Ar/^{39}Ar$ ages from the Elefantes section. E & F) Zircon seperates with Concordia age from Serra de Neve.

Namibe flows; $^{40}Ar/^{39}Ar$

In the Southern Namibe sections an area around an emergent sub-marine to subaerial volcano situated at Ponta Negra was chosen for sampling fresh material for analysis. $^{40}Ar/^{39}Ar$ data for two samples is presented in Figure 7, highlighting a younger age still at around 81-82 Ma. K-Ar dating of lava flows slightly further north in the Namibe Basin (inland from Bentiaba section) recorded slightly older dates of 88Ma ± 1.3Ma (Statoil internal report). The majority of the Namibe section volcanics are lava flows, hyaloclastites and small eruptive centres, often nucleated along NW-SE trending segmented fault arrays, like that at Ponta Negra which feed lava/hyaloclastie sequences. Again the direct relationship with the stratigraphy is very evident. The flows are found sitting immediately above the regionally extensive transgressive Ponta Salinas Fm in most studied sections, and ammonites collected during the course of this study confidently assign this unit to the latest Cenomanian into Turonian, possibly extending into the Early Coniacian. Fauna present and dated include *Gaudryceras isovokyense* (Collignon, 1964), *Calycoceras (Calycoceras) naviculare* (Mantell, 1822) *Metoicoceras geslinianum* zone, *Metoicoceras geslinianum* (d'Orbigny, 1850) *Metoicoceras geslinianum* zone (Figure 8). Sediments and fauna found sitting transgressively above the volcanic flows at all Namibe locations have been confidently dated to the Latest Santonian to Early Campanian.

The fauna and age assignments recorded in our study are in keeping with existing stratigraphic studies in the Namibe Basin (e.g. Carvalho and Soares, 1961; Cooper, 1972, 1973, 1978, 2003 a&b; Strganac *et al* 2014). Cooper reports a Late Turonian to Early Coniacian ammonite fauna from the Salinas Fm at Bentiaba immediately below the volcanics, and a Middle Santonian to Early Campanian ammonite fauna sitting immediately above the volcanics (Cooper 2003 a&b). A recent study by Strganac *et al* (2014) have further constrained the age of the volcanics in Namibe based on a detailed section at Bentiaba using carbon isotope, magnetostratigrphy and $^{40}Ar/^{39}Ar$ methods. $^{40}Ar/^{39}Ar$ dating of the main flow at this section gave a radiometric age of 84.6 ± 1.5 Ma, and identification of the Cenomanian-Turonian Boundary Event in the sediments directly underneath giving an age of 93.9Ma (Ocean Anoxic Event 2). Sediments sitting above the volcanics are dated from the Santonian to Early Campanian. The dating of the volcanic centre at Ponta Negra in this study extends the duration of volcanism to 81-82 Ma, with the younging of the volcanics as we move south.

[Figure 7] $^{40}Ar/^{39}Ar$ age analysis of the Ponta Negra volcanic centre and associated flows.

[Figure 8] Ammonites found in Namibe section below volcanics: a) 11 *Calycoceras (Calycoceras) naviculare* (Mantell, 1822) Upper Cenomanian, *Metoicoceras geslinianum* Zone. b) *12 Metoicoceras geslinianum* (d'Orbigny, 1850) Upper Cenomanian, *Metoicoceras geslinianum* Zone.

Summary of geochronological data

The three main sections sampled during this study have shown a progressive younging of ages from the northernmost Sumbe section in the Kwanza Basin through to the southernmost sections in the Namibe Basin. Table 1 provides a summary of the age data from this study. A plot of age vs distance from Namibe as well as the approximate locations of the volcanic events within the stratigraphy is given in figure 9. This provides a useful visual assessment of this data in the context of the margin. Volcanic events are occurring within the Early to Late Cretaceous, along this margin with a general younging towards Namibia and the site of the emerging Walvis Ridge relating to the continued expression of the Tristan da Cunha hotspot trail away from the Parana-Entendeka large igneous province. These volcanic events, although small, provide vital age information about the margin and are worthy of further consideration in respect of their distribution in time and space in the context of the separation of Africa with South America.

[Table 1] Summary of geochronological data presented in this contribution.

[Figure 9] Younging age progression of the Geochronology data presented in this study with stratigraphic location indicated. 1 – Kwanza Basin, 2 Benguela Basin, 3 Namibe Basin

Plate reconstruction, unzipping and volcanic distribution

Ocean basin geometries are best reconstructed by a combination of magnetic isochrons and fracture zones. Unfortunately, vast amounts of seafloor spreading in the South Atlantic occurred during the Kiaman Normal Superchron between 121 Ma (chron MO) and 83.5 Ma (anomaly 24) (Cande & Kent 1995). The opening history of the South Atlantic is therefore partly based on only fracture zone geometries and interpolation between 121 and 83.5 Ma. Figure 10 shows plate reconstructions for the time periods indicated by the volcanic events presented in this study. Also indicated are the main distribution of the Paraná-Etendeka preserved onshore exposures, and the distribution of the younger volcanic rocks from this study.

[Figure 10] Left hand diagrams: Plate reconstructions of the central South Atlantic (updated from Torsvik et al. 2009) in an absolute mantle reference frame (Doubrovine et al. 2012) Onshore volcanic sections highlighted with a star. Right hand images highlight the relative distribution of the volcanic events and locations of offshore volcanic anomalies.

The Paraná-Etendeka large igneous province (LIP) erupted above the plume generation zone (e.g. the PGZ, thick red stippled line on Figure 10, which is the 0.9% slow contour in the *s10mean* tomography model of Doubrovine et al (2016) at around 134-135 Ma (see Svensen et al. 2017). Seafloor spreading started south of the Florianopolis Fracture Zone at ~130 Ma whilst the area to the north underwent pre-break extension until ~112-110 Ma when a single subtropical syn-rift Aptian salt basin (preserved on the Brazilian, Angolan, Congo and Gabon continental shelves) was dissected by seafloor spreading (Torsvik et al., 2009; Kukla et al., 2018). At ~100 Ma, the salt basins (Brazilian-Angolan margins) were separated by ~700 km of oceanic crust and South America is dominated by a strong component of westerly motion relative to the mantle (black thick arrows). From 100 to 81 Ma around 1200 km of westerly drift of South America (subduction rollback) corresponds 6.3 cm/yr of longitudinal motion whilst Africa is almost 'fixed' in longitude over the same time interval (see black absolute velocity arrows in figure 10). The white arrows at 92 and 81 Ma (figure 10) show the relative motion paths for three points on the African margin (relative South America) and denote the motion paths from 100 to 92 Ma (92 Ma reconstruction) and 90 to 81 Ma (81 Ma reconstruction). Additionally the NW-SE trending volcanic bodies are also developed on ocean crust picked out using seismic and potential field data. Seismic stratigraphy also clearly shows the offshore Sumbe volcanics young southwards (*in-house* Statoil data). These observations are consistent with the timings of separation as listed above, and the ages presented in this study.

The offshore structural domain and seismic stratigraphy work (e.g. Higgins et al submitted) clearly shows that the rift offshore Angola is "unzipping" and propagating from north to south. The age of this unzipping seems to be post salt (Albian) in age south of the city of Namibe, but is older than that in the north. Interestingly, the Inner Santos rift is clearly propagating from south to north around this time, with the Sao Paolo plateau rifted fragment caught in between (cf. Scotchman et al 2011). There are younger than Paraná-Etendeka volcanic events found on the Brazilian side. Ages around 100-102 Ma are reported for the Cabo Magmatic Province (Nascimento et al., 2003), which is somewhat to the north of this region when looking at the reconstructions. This seems to also be corroborated by palaeomagnetic data (e.g. Font et al., 2009). Younger ages of ~90Ma (mostly K-Ar) have been noted in the Potiguar Basin (equatorial region) and as some ages from south of Brazil (Mizusaki et al., 2002; Souza et al., 2003). The alkaline centre at Monte de Trigo Island in a geographically very close proximity section on the Brazilian margin has a reported age of 86.6 Ma ($^{40}Ar/^{39}Ar$, Enrich et al., 2009). Other alkaline intrusions (dykes and plugs) with ages of 82 Ma as well as younger examples are found intersecting the basement of the Santos Basin (Guedes et al., 2005), which would also be geographically at a similar section along the Brazilian side of the South Atlantic Margin. Additionally, kimberlites and phlogopite bearing picrites are reported with age ranges from 91-78 Ma within the Paranaíba Igneous Province (Guarino et al., 2013), which are occurring inland from the rifting margin, with some similar young kimberlites pulses (90 ± 10 Ma and 60 ± 10 Ma) preserved inland on the African margin (e.g. Tappe et al., 2018). These all give testament of a series of younger than Paraná-Etendeka magmatic events, albeit of relatively low volumes, that occur as the rifting continents parted. The new ages presented in this contribution clearly highlight that more geochronological information can be yielded from the Late Cretaceous and can provide valuable geographical constraints on magmatic events in the context of the continental separation of Africa from South America.

Conclusions and closing remarks

This contribution has introduced the geochronological and plate tectonic significance of Early to Late Cretaceous magmatic events found along the Angolan section of the West African margin. Three main igneous events are found and have been placed into their spatial and temporal occurrences along the margin with the following main conclusions and comments:

- The oldest of the events is found along a coastal section (Casa Branca) south of the city of Sumbe, termed the Sumbe Volcanics, which erupted in a shallow sub-marine environment at around 100 Ma. The main rock types consist of pillow basalts and hyaloclastites which interact with and are also interbedded between fossiliferous mixed carbonate-clastic shelfal sediments of Late Albian age. The volcanics at this location are “sealed” by sediments dated as latest Albian.
- The next event occurred at around 91 Ma within the Benguela Basin and is found spanning an area from a large volcanic centre, Sierra de Neve 65 km inland from the coast, out to a coastal section between Baia dos Elefantes and Binga. The section is termed the Sierra de Neve-Baia dos Elefantes lineament. The rocks contain both basic to evolved units, with a full suite from intrusives to lava flows that have flowed into a palaeo coastal environment of shore face and shallow marine sediments deposited in water depths of between 0-200 m. Sediments underlying the main volcanic events at the coast have been dated as Latest Albian.
- The final event is as young as 82-81 Ma considering the new $^{40}Ar/^{39}Ar$ ages presented here. With the additional associated age constraints this pulse spans between 88-81Ma, and is found as lava flows, hyaloclasties and localised plugs, in a coastal zone north of the town Namibe, termed the Namibe volcanics in this contribution. These commonly transition from lava flows from sub-aerial into shoreface and shallow marine environments as well as submarine eruptions that emerge to form sub-aerial volcanoes. These sections are underlain by well dated fossiliferous sediments of Turonian-Early Coniacian age, and overlain by sediments dated as Middle Santonian to Early Campanian age
- $^{40}Ar/^{39}Ar$, U/Pb and paleontological constraints have been used in combination with a regionally understood stratigraphic sequence to place these three magmatic events into order. With a trend from north to south along the coast in terms of relative emplacement age.
- Plate reconstructions, including the location of the main salt basins, have been presented to highlight the unzipping of the margin and the location of these magmatic events that migrate southwards to the proto Walvis ridge.
- Similar constraints on the Early to Late Cretaceous volcanics found along the equivalent sections along the Brazilian side of the South American Margin will be need to fully assess the role of this late stage magmatism as the African and South American continents separate.

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Figure and table captions

Figure 1. a) Location maps of SW Angola showing the 3 main study locations. b) Casa Branca beach section, Sumbe, Kwanza Basin. c) Baía dos Elefantes and Serra de Neve, Benguela Basin. d) Bentiaba, Ponta Negra, Canico, Piambo and Uah sections, Namibe Basin. Additional features offshore indicated.

Figure 2 Stratigraphic context of the Cretaceous lithologies present along the Angolan margin. Section are generalised for the Kwanza Basin (left) and onshore Namibe Basin (right) (see also Gindre-Chanu et al., 2014).

Figure 3. a) View looking North along the Sumbe volcanics section at Casa Branca, Kwanza Basin. In view are pillow basalts and hyaloclastites interbedded with and overlain by a mixed carbonate-clastic slope succession of Latest Albian age. b) Example of exceptionally fresh olivine rich basalt from the Sumbe volcanics, Casa Branca section, Kwanza Basin. c) View from the edge of the Serra de Neve complex, Southern Benguela Basin. d) Large feldspar rich phonolite from the central intrusions within the Serra de Neve complex, Southern Benguela Basin . e) Coastal exposure at Baia dos Elefantes, Benguela Basin. At this location lavas overly shelfal to slope ammonite bearing carbonates of Latest Aptian age. f) close up of feldspar rich phonolite lava flow, as similar facies to that found in d. Baía dos Elefantes sections, Benguela Basin. g) Coastal section at Ponte Negra, Namibe Basin, comprising reowked hyaloclastits, invasive flows, pillows and emergent volcanics immediately overlying sediments of the Salinas Fm of Coniacian to Santonian age. h) Hyaloclastites exposed at the Ponta Negra section, Namibe Basin.

Figure 4 Total alkalis vs. silica diagrams for all analysed TAS classification diagram of the samples from this contribution. Overlain on top of a selection of representative rocks from the margin (after Comin-Chiaramonti et al., 2011). Numbered fields (volcanic-intrusive): 1) picrobasalt-picrogabbro; 2) basaltgabbro; 3) basaltic andesite-gabbrodiorite; 4) andesite-diorite; 5) dacite-granodiorite; 6) rhyolite-granite; 7) trachybasalt- monzogabbro; 8) basaltic trachyandesite–monzodiorite; 9) trachyandesite-monzonite; 10) trachydacite–quartz monzonite; 11) trachyte-syenite; 12) basanite/ tephrite–foid gabbro; 13) phonotephrite–foid monzogabbro; 14) tephriphonolite–foid monzosyenite; 15) phonolite–foid syenite; 16) foidite-foidolite (see also Comin-Chiaramonti et al., 2011) .

Figure 5. Geochronology of the Casa Branca Beach Section, Sumbe. a & b) $^{40}Ar/^{39}Ar$ age with good overlapping plateaux and inverse isochron ~101.5 Ma. C & D) Ammonites within interpillow sediments. e, f & g) Ammonites from sediments directly above the volcanics - Mortoniceras (Angolaites) gregoryi (Spath, 1922), Upper Upper Albian, M. (S.) rosratum subzone (vicina horizon of Tavares et al., 2007 – giving an age of 99 Ma).

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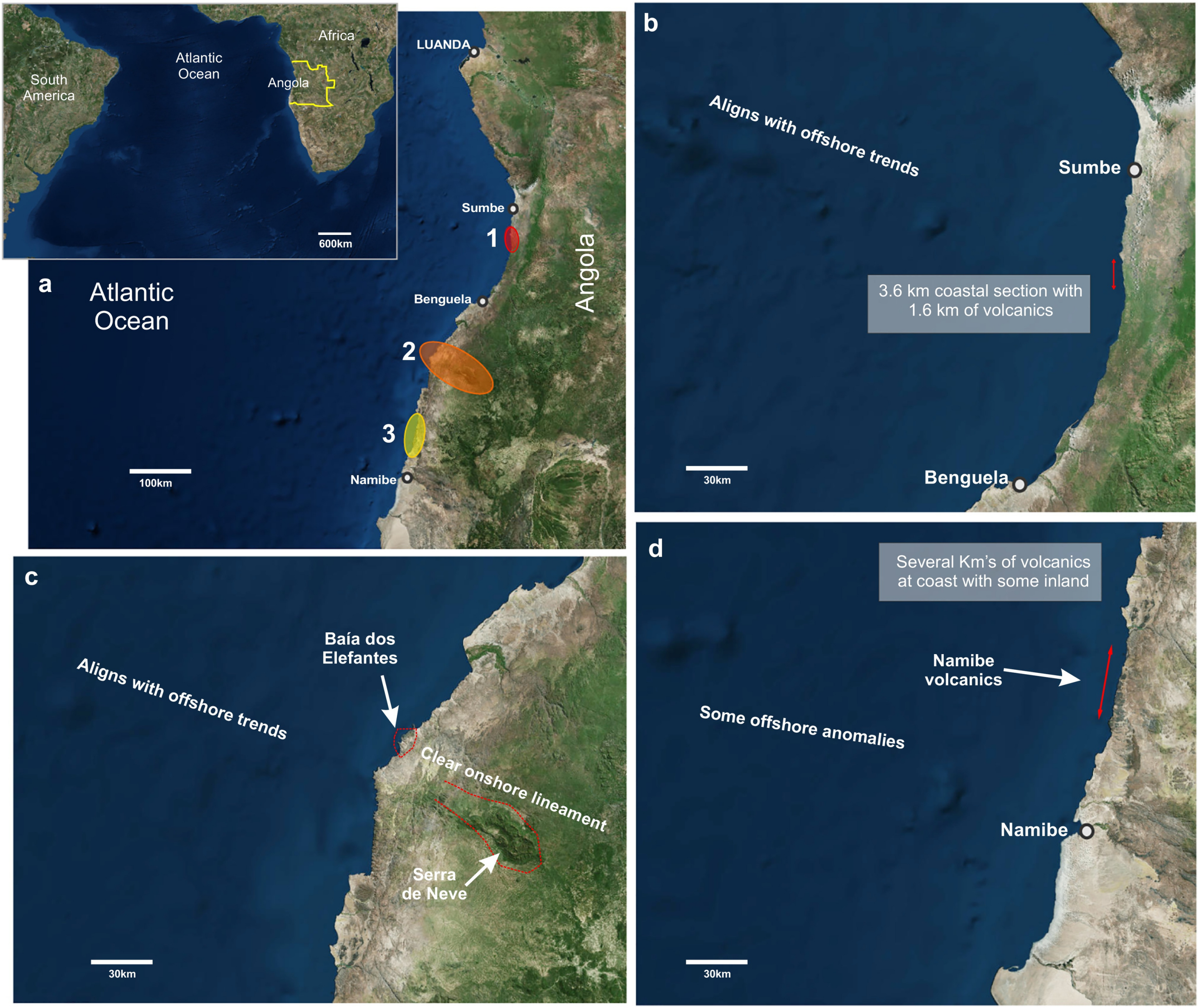


Africa
Atlantic Ocean
South America
Angola
600km
LUANDA
Sumbe
1
Benguela
2
3
Namibe
a
Atlantic Ocean
Angola
100km
b
Aligns with offshore trends
Sumbe
3.6 km coastal section with 1.6 km of volcanics
30km
Benguela
c
Baía dos Elefantes
Aligns with offshore trends
Clear onshore lineament
Serra de Neve
30km
d
Several Km's of volcanics at coast with some inland
Namibe volcanics
Some offshore anomalies
Namibe
30km

Figure 1

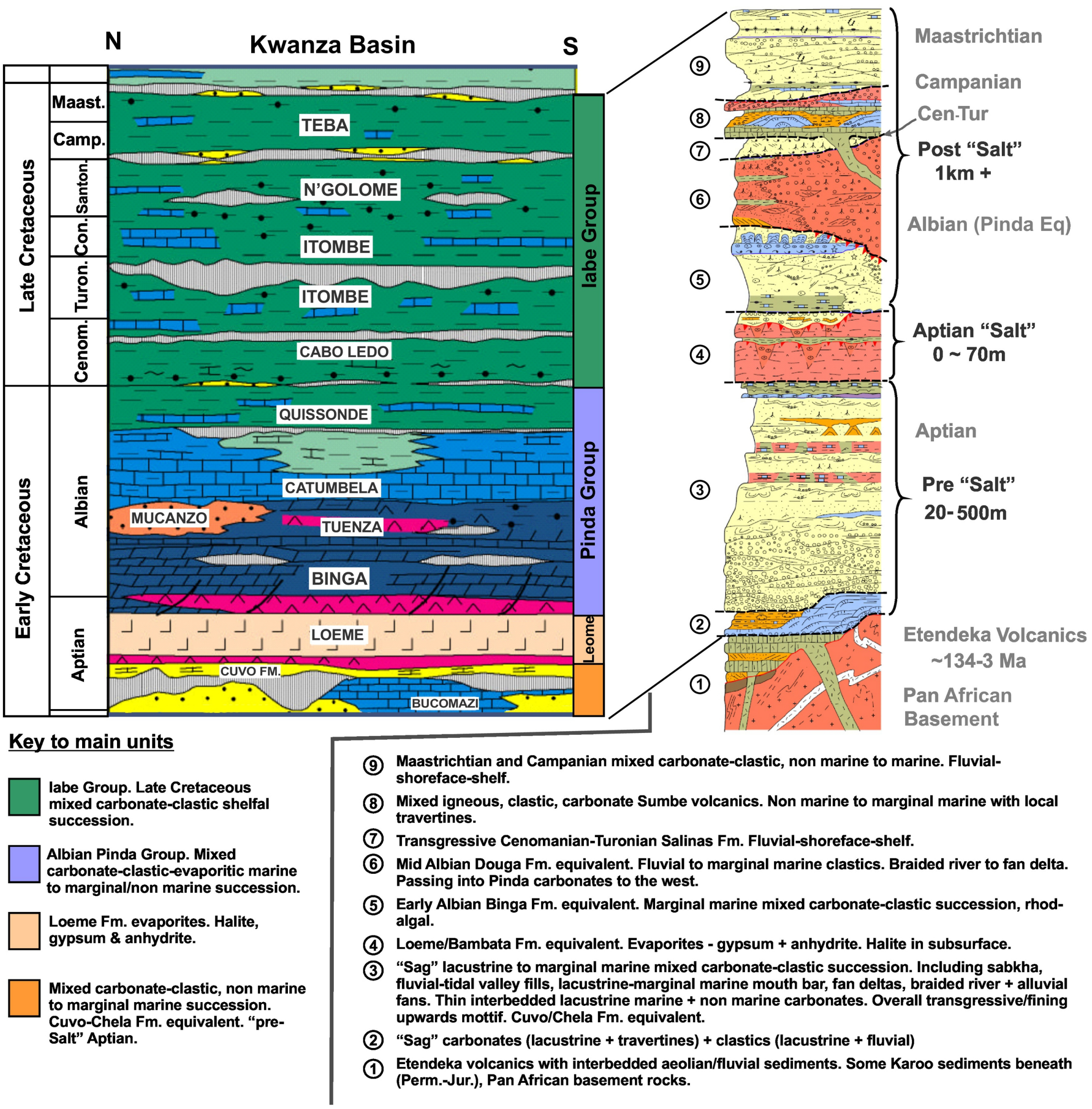
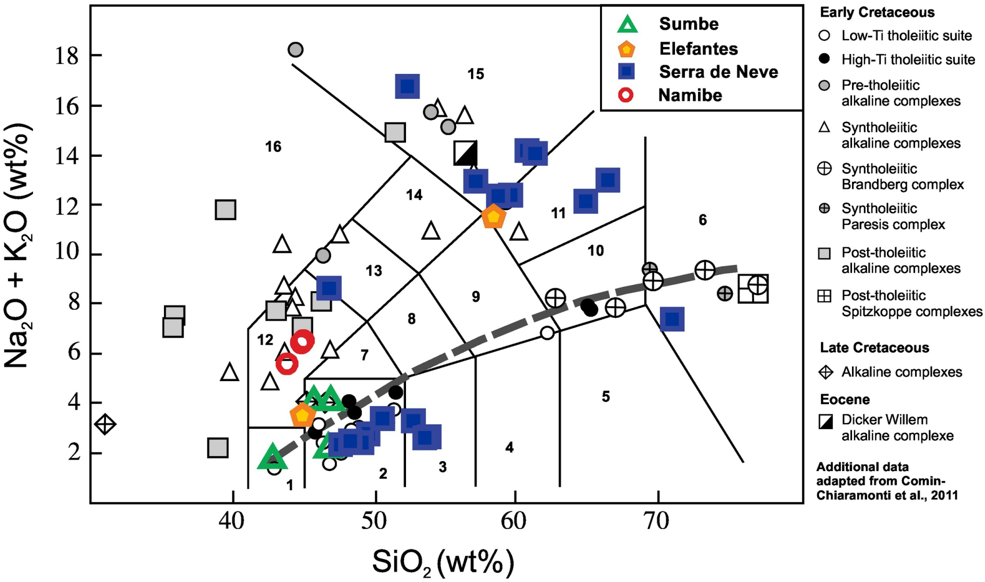

N
Kwanza Basin
S
Late Cretaceous
Early Cretaceous
Maast.
Camp.
Santon.
Con.
Turon.
Cenom.
Albian
Aptian
TEBA
N'GOLOME
ITOMBE
ITOMBE
CABO LEDO
QUISSONDE
CATUMBELA
MUCANZO
TUENZA
BINGA
LOEME
CUVO FM.
BUCOMAZI
Iabe Group
Pinda Group
Leome
Maastrichtian
Campanian
Cen-Tur
Post "Salt"
1km +
Albian (Pinda Eq)
Aptian "Salt"
0 ~ 70m
Aptian
Pre "Salt"
20-500m
Etendeka Volcanics
~134-3 Ma
Pan African
Basement
9
8
7
6
5
4
3
2
1
Key to main units
Iabe Group. Late Cretaceous mixed carbonate-clastic shelfal succession.
Albian Pinda Group. Mixed carbonate-clastic-evaporitic marine to marginal/non marine succession.
Loeme Fm. evaporites. Halite, gypsum & anhydrite.
Mixed carbonate-clastic, non marine to marginal marine succession. Cuvo-Chela Fm. equivalent. "pre-Salt" Aptian.
9 Maastrichtian and Campanian mixed carbonate-clastic, non marine to marine. Fluvial-shoreface-shelf.
8 Mixed igneous, clastic, carbonate Sumbe volcanics. Non marine to marginal marine with local travertines.
7 Transgressive Cenomanian-Turonian Salinas Fm. Fluvial-shoreface-shelf.
6 Mid Albian Douga Fm. equivalent. Fluvial to marginal marine clastics. Braided river to fan delta. Passing into Pinda carbonates to the west.
5 Early Albian Binga Fm. equivalent. Marginal marine mixed carbonate-clastic succession, rhod-algal.
4 Loeme/Bambata Fm. equivalent. Evaporites - gypsum + anhydrite. Halite in subsurface.
3 "Sag" lacustrine to marginal marine mixed carbonate-clastic succession. Including sabkha, fluvial-tidal valley fills, lacustrine-marginal marine mouth bar, fan deltas, braided river + alluvial fans. Thin interbedded lacustrine marine + non marine carbonates. Overall transgressive/fining upwards mottif. Cuvo/Chela Fm. equivalent.
2 "Sag" carbonates (lacustrine + travertines) + clastics (lacustrine + fluvial)
1 Etendeka volcanics with interbedded aeolian/fluvial sediments. Some Karoo sediments beneath (Perm.-Jur.), Pan African basement rocks.

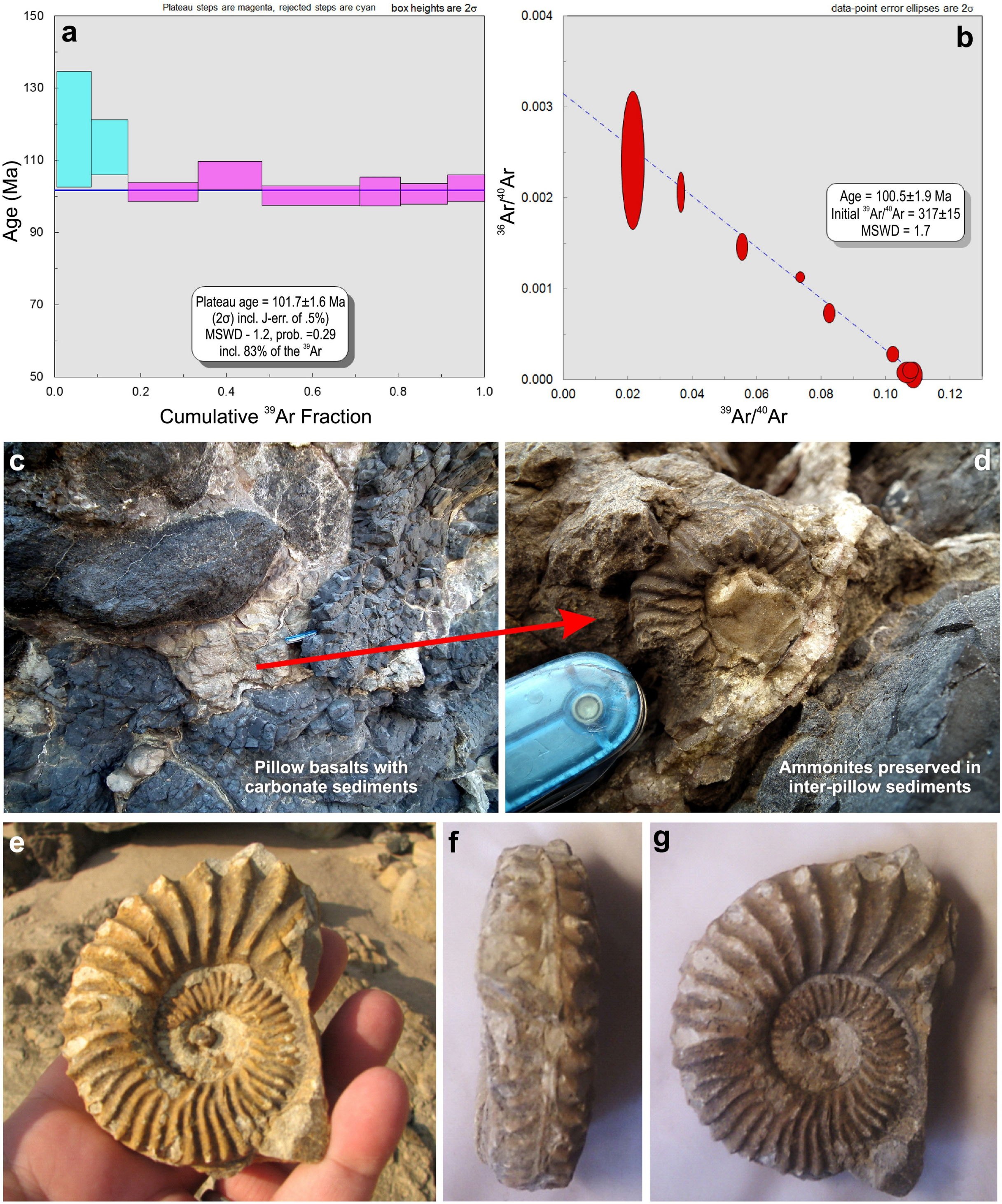
Figure 2

Figure 3



Sumbe
Elefantes
Serra de Neve
Namibe
Early Cretaceous
Low-Ti tholeiitic suite
High-Ti tholeiitic suite
Pre-tholeiitic alkaline complexes
Syntholeiitic alkaline complexes
Syntholeiitic Brandberg complex
Syntholeiitic Paresis complex
Post-tholeiitic alkaline complexes
Post-tholeiitic Spitzkoppe complexes
Late Cretaceous
Alkaline complexes
Eocene
Dicker Willem alkaline complexe
Additional data adapted from Comin-Chiaramonti et al., 2011
Na2O + K2O (wt%)
SiO2 (wt%)

Figure 4



Plateau steps are magenta, rejected steps are cyan
box heights are 2σ
a
Age (Ma)
Plateau age = 101.7±1.6 Ma
(2σ) incl. J-err. of .5%)
MSWD - 1.2, prob. =0.29
incl. 83% of the 39Ar
Cumulative 39Ar Fraction
data-point error ellipses are 2σ
b
36Ar/40Ar
Age = 100.5±1.9 Ma
Initial 39Ar/40Ar = 317±15
MSWD = 1.7
39Ar/40Ar
c
Pillow basalts with
carbonate sediments
d
Ammonites preserved in
inter-pillow sediments
e
f
g

Figure 5

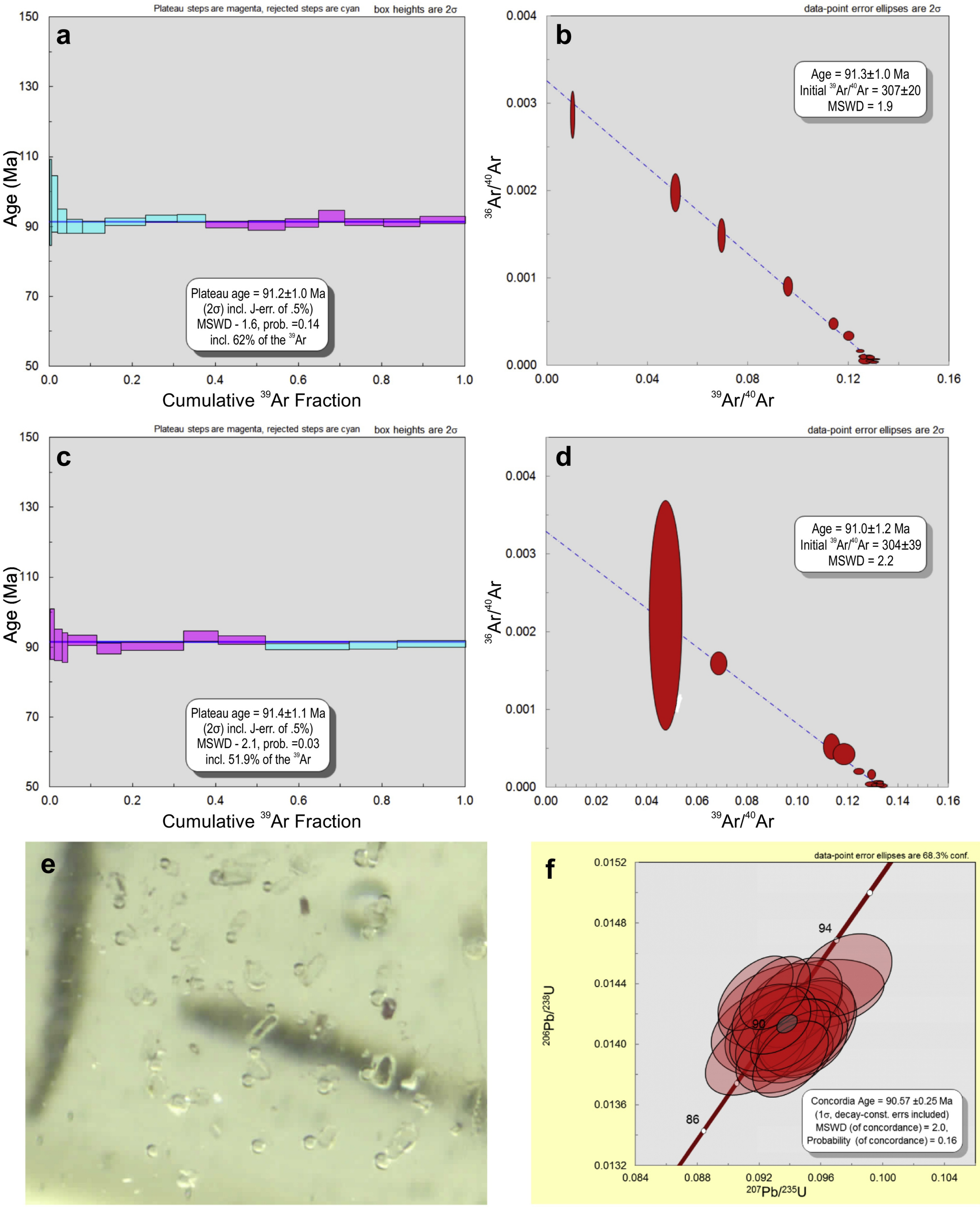

a
Plateau steps are magenta, rejected steps are cyan
box heights are 2σ
Age (Ma)
Cumulative ^{39}Ar Fraction
Plateau age = 91.2±1.0 Ma
(2σ) incl. J-err. of .5%)
MSWD - 1.6, prob. =0.14
incl. 62% of the ^{39}Ar
b
data-point error ellipses are 2σ
Age = 91.3±1.0 Ma
Initial ^{39}Ar/^{40}Ar = 307±20
MSWD = 1.9
^{36}Ar/^{40}Ar
^{39}Ar/^{40}Ar
c
Plateau steps are magenta, rejected steps are cyan
box heights are 2σ
Age (Ma)
Cumulative ^{39}Ar Fraction
Plateau age = 91.4±1.1 Ma
(2σ) incl. J-err. of .5%)
MSWD - 2.1, prob. =0.03
incl. 51.9% of the ^{39}Ar
d
data-point error ellipses are 2σ
Age = 91.0±1.2 Ma
Initial ^{39}Ar/^{40}Ar = 304±39
MSWD = 2.2
^{36}Ar/^{40}Ar
^{39}Ar/^{40}Ar
e
f
data-point error ellipses are 68.3% conf.
^{206}Pb/^{238}U
^{207}Pb/^{235}U
Concordia Age = 90.57 ±0.25 Ma
(1σ, decay-const. errs included)
MSWD (of concordance) = 2.0,
Probability (of concordance) = 0.16

Figure 6

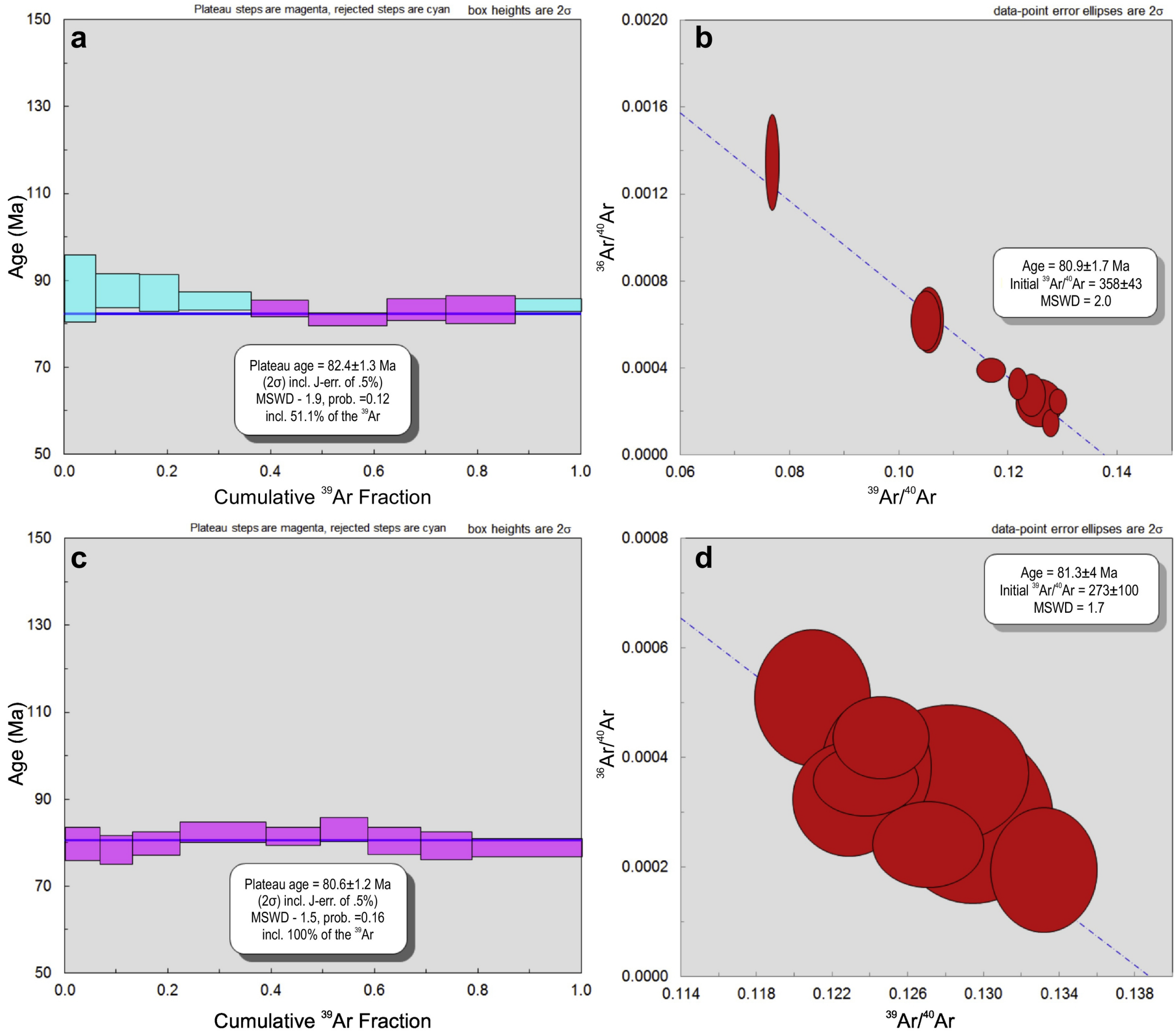

Plateau steps are magenta, rejected steps are cyan
box heights are 2σ
a
Age (Ma)
Plateau age = 82.4±1.3 Ma
(2σ) incl. J-err. of .5%)
MSWD - 1.9, prob. =0.12
incl. 51.1% of the 39Ar
Cumulative 39Ar Fraction
data-point error ellipses are 2σ
b
36Ar/40Ar
Age = 80.9±1.7 Ma
Initial 39Ar/40Ar = 358±43
MSWD = 2.0
39Ar/40Ar
Plateau steps are magenta, rejected steps are cyan
box heights are 2σ
c
Age (Ma)
Plateau age = 80.6±1.2 Ma
(2σ) incl. J-err. of .5%)
MSWD - 1.5, prob. =0.16
incl. 100% of the 39Ar
Cumulative 39Ar Fraction
data-point error ellipses are 2σ
d
36Ar/40Ar
Age = 81.3±4 Ma
Initial 39Ar/40Ar = 273±100
MSWD = 1.7
39Ar/40Ar

Figure 7

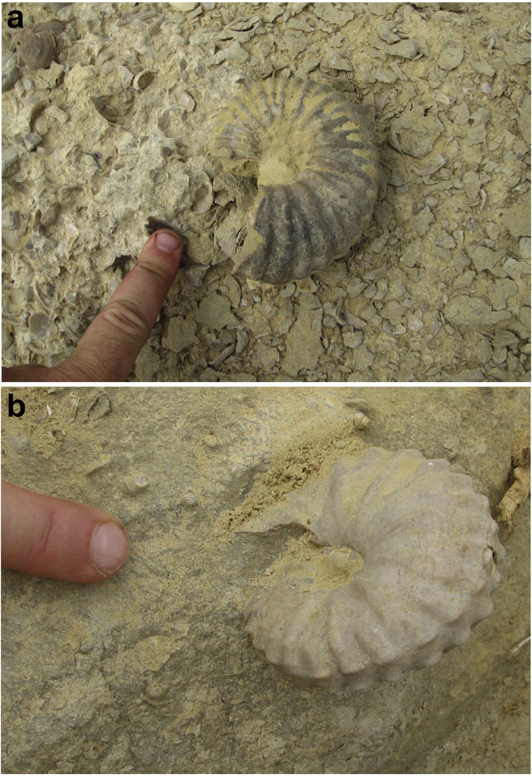
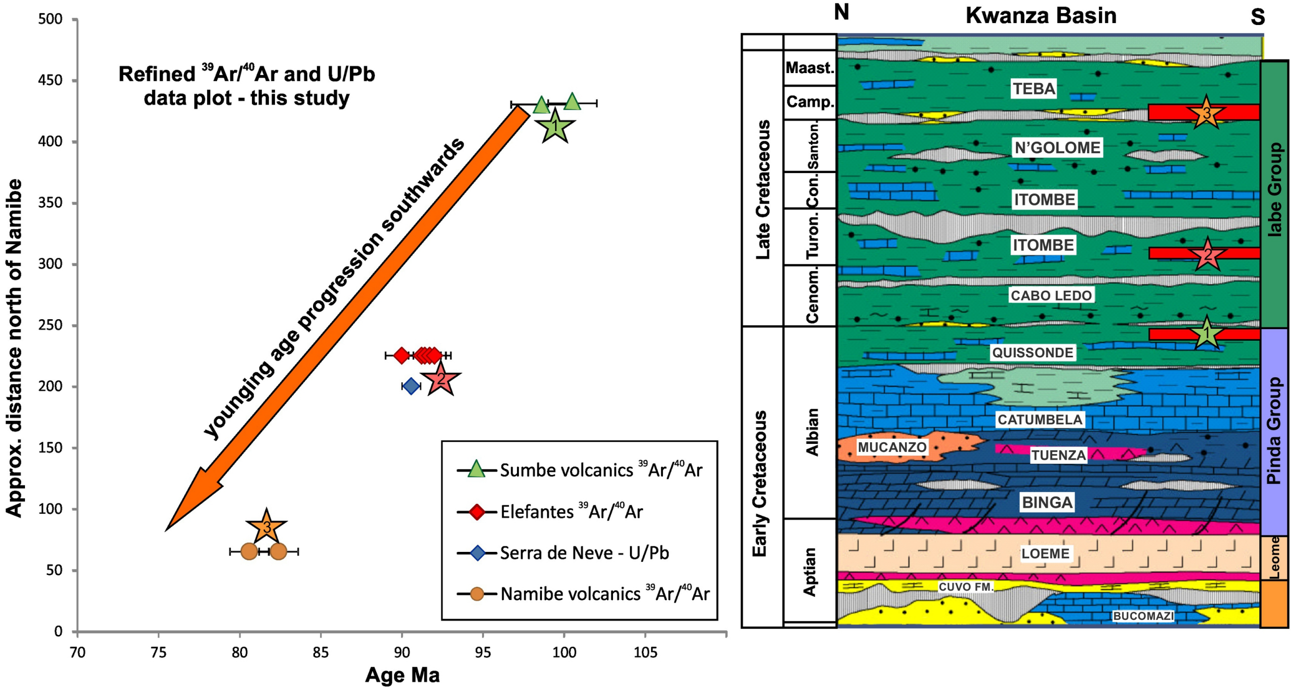
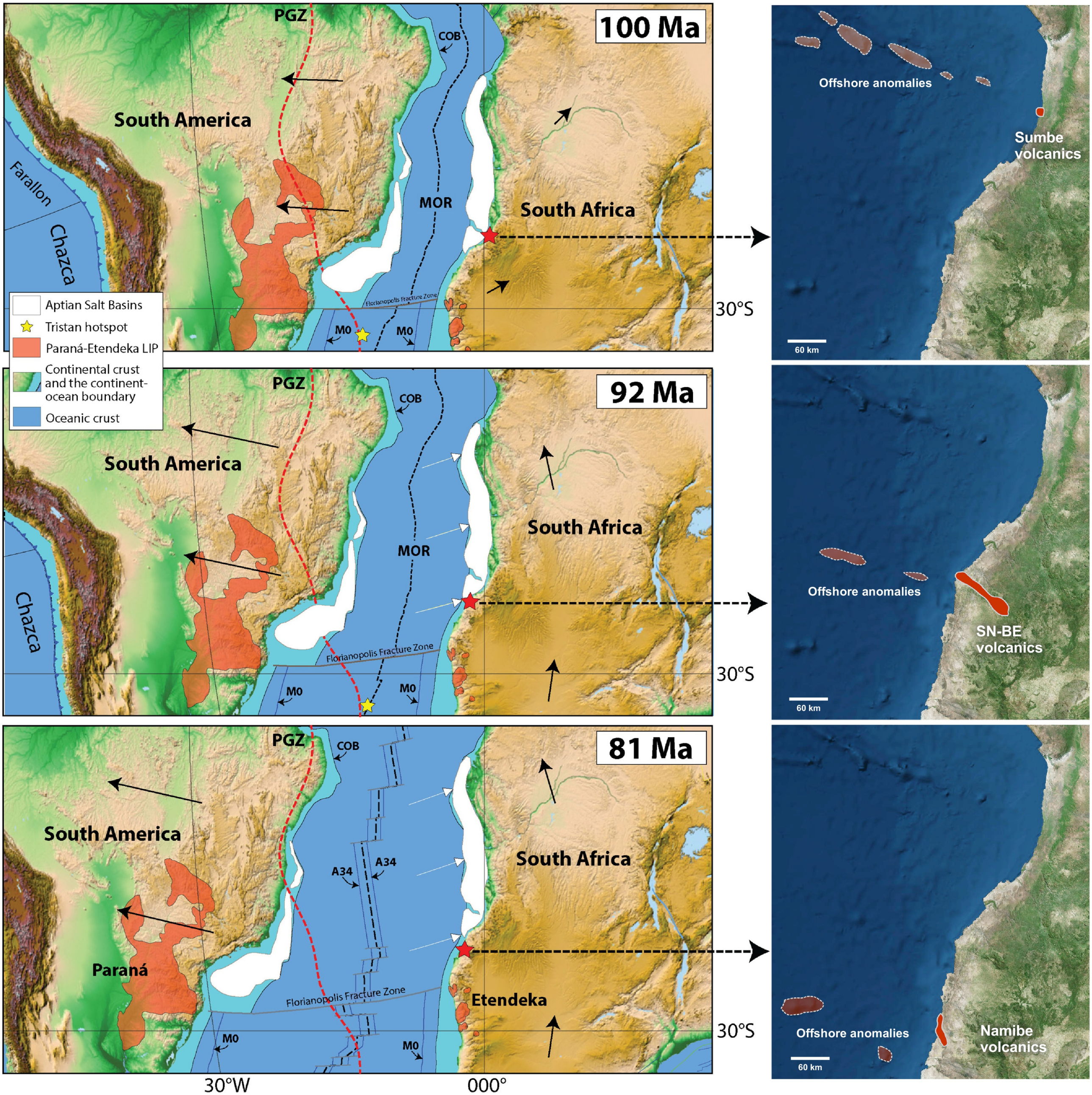


Figure 8



Refined $^{39}Ar/^{40}Ar$ and U/Pb data plot - this study
younging age progression southwards
Approx. distance north of Namibe
Age Ma
Sumbe volcanics $^{39}Ar/^{40}Ar$
Elefantes $^{39}Ar/^{40}Ar$
Serra de Neve - U/Pb
Namibe volcanics $^{39}Ar/^{40}Ar$
N
Kwanza Basin
S
Late Cretaceous
Early Cretaceous
Maast.
Camp.
Santon.
Con.
Turon.
Cenom.
Albian
Aptian
TEBA
N'GOLOME
ITOMBE
ITOMBE
CABO LEDO
QUISSONDE
CATUMBELA
MUCANZO
TUENZA
BINGA
LOEME
CUVO FM.
BUCOMAZI
Iabe Group
Pinda Group
Leome

Figure 9



100 Ma
PGZ
COB
South America
Farallon
Chazca
MOR
South Africa
Florianopolis Fracture Zone
M0
M0
30°S
Offshore anomalies
Sumbe volcanics
60 km
Aptian Salt Basins
Tristan hotspot
Paraná-Etendeka LIP
Continental crust and the continent-ocean boundary
Oceanic crust
92 Ma
PGZ
COB
South America
Chazca
MOR
South Africa
Florianopolis Fracture Zone
M0
M0
30°S
Offshore anomalies
SN-BE volcanics
60 km
81 Ma
PGZ
COB
South America
A34
A34
South Africa
Paraná
Florianopolis Fracture Zone
Etendeka
M0
M0
30°S
Offshore anomalies
Namibe volcanics
60 km
30°W
000°

Figure 10